Contact Condition Detection by Tactile Sensor

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Nomenclature

\[ \mathbf{f} = (f_x, f_y, f_z) \] : force vector

\[ \mathbf{e} = (e_x, e_y, e_z) \] : strain vector

\[ A \] : coefficient matrix

\[ a_{ij} \] : elements if coefficient matrix

\[ B \]

\[ l \] : interval of the sensor elements

\[ \mathbf{r}_i \] : position vector of the \( i \)-th sensor element

\[ \mathbf{R} \] : position vector of the object

\[ \mathbf{M} \] : moment vector of the object

\[ \mathbf{M}_G \] : moment vector of the object at the gravity point
ABSTRACT

This paper describes a three-axial tactile matrix sensor capable of detecting both vertical force and shear force on the same plane. The sensor comprises twelve force sensor elements, each equipped with the strain gauges. We perform experimental evaluations of the relationship between the three axial forces and the observed strain values. To compare applied loads with the predicted forces, results show that the uncertainty of the predicted forces is relatively very small compared to the rating force value. Furthermore, we suggest method for detecting slippage using this matrix tactile sensor. We calculate with a force sensor the friction coefficient by measuring the normal and tangential forces that occur when the object starts moving.

INTRODUCTION

When developing a dexterous robot manipulator, the tactile sensor presents a fundamental problem because tactile sensing gives the manipulator much information for interacting physically with the environment in a non-conventional or non-structured manner [1][2]. To solve this problem, many designs for tactile sensors have been investigated [3][4]. The tactile sensor we are developing can measure forces using strain gauges. We have produced a prototype sensor five times larger than those used in practice [5][6], and this paper examines the attributes of this tactile sensor. We clarify the relations experimentally between the applied loads and the observed strains. These relations make it possible to predict forces on the basis of the observed strain values. And we analyze the uncertainty of the forces predicted by the observed strain values. Results show that the uncertainty of predicted forces are relatively very small compared to the rating force values. Furthermore, we demonstrate in a simulation that this sensor can detect the motion of a contacted object.

RELATION BETWEEN FORCES AND STRAINS

This sensor element detects the three-axial forces as the changes in electrical resistance in the strain gauges attached to the surface of each sensor. Figure 1 shows the shape of a single sensor element. The strain gauges on the upper side of the board mainly detect contact force. The sharing forces are mainly detected by the strain gauges attached to the legs. In Figure 2, the arrowhead a, b, c and d shows these strain gauges. The tactile sensor consists of 12 sensor elements, as illustrated in Figure 3.
To clarify the relations between the three axial \((X, Y, Z)\) forces and measured strains, the experiments are conducted under the following two conditions. The first condition is that the load is applied in only one direction. The relations of this condition are depicted in Figure 4. The other condition is that the loads are applied simultaneously in three directions as Table 1.

Figure 4 shows that linear relations exist between the forces and the strains when the load is applied in one direction. However, even though the loads are applied in three directions, there is no exact linear relation between strain and load. Therefore, we propose the following three experimental relations between the applied load vector \(\mathbf{f} = (f_x, f_y, f_z)\) and the measured strain vector \(\mathbf{e} = (e_x, e_y, e_z)\). Moore-Penrose pseudo inverse matrix gives us the coefficient matrix \(A\).

\[ \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} \]  
\[ (1) \]

\[ \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \end{bmatrix} \begin{bmatrix} e_x \\ e_y \\ e_z \\ e_x e_y \\ e_x e_z \\ e_y e_z \end{bmatrix} \]  
\[ (2) \]
To compare these three relations, we calculated SN ratio. The results of SN ratio analysis are displayed in Figure 5. SN ratio indicates that Equation (2) is the best relation between applied actual loads and predicted forces by the observed strain values. Figure 6 shows the relation between applied actual sample loads and predicted forces used in Equation (2), demonstrating that the predicted forces agree very well with the actual loads.

$$
\begin{bmatrix}
  f_x \\
  f_y \\
  f_z 
\end{bmatrix} =
\begin{bmatrix}
  a_{11} & a_{12} & a_{13} & 0 & a_{15} & 0 \\
  a_{21} & a_{22} & a_{23} & a_{24} & 0 & 0 \\
  a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & 0 
\end{bmatrix}
\begin{bmatrix}
  e_x \\
  e_y \\
  e_z \\
  e_y e_z \\
  e_x e_y
\end{bmatrix}
$$

(3)

Table 1. Applied loads

<table>
<thead>
<tr>
<th>( f_x (N) )</th>
<th>( f_y (N) )</th>
<th>( f_z (N) )</th>
<th>( f_x (N) )</th>
<th>( f_y (N) )</th>
<th>( f_z (N) )</th>
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<td>0</td>
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<td>29.4</td>
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<td>-9.8</td>
<td>9.8</td>
<td>29.4</td>
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<td>29.4</td>
</tr>
</tbody>
</table>

Figure 5 SN Ratio
ANALYSIS OF UNCERTAINTY

This section addresses the uncertainty of the predicted force values. It is necessary to investigate the uncertainty analysis for developing the sensor. In the case of this sensor element, the uncertainty of the predicted force is caused by the repetition, the zero point variation, the hysteresis, the interpolation and the temperature [7].

The repetition uncertainty belongs to type A and can be estimated statistically. The zero point variation uncertainty and the hysteresis uncertainty are applied Gaussian distributions (type B). The interpolation uncertainty belongs to type A, and it is calculated using the SN ratio in the previous section. The temperature uncertainty belongs to type B. We applied the rating loads to a sensor element at the temperature of 21 and 27 degree Centigrade, measured the strain values, predicted forces using Equation (2), and then we estimate the uncertainty using ANOVA.

We get the expansion combination uncertainty based on these uncertainty values. The uncertainty analysis results are displayed in Table 2. The ratio of the expansion combination uncertainty and rating force is shown in the last row, indicating that the reliability of the predicted force value is valid.

Table 2. Uncertainty Values

<table>
<thead>
<tr>
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<th>$f_x$</th>
<th>$f_y$</th>
<th>$f_z$</th>
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<tr>
<td>Repetition</td>
<td>0.06390N</td>
<td>0.04197N</td>
<td>0.03230N</td>
</tr>
<tr>
<td>Zero Point</td>
<td>0.02525N</td>
<td>0.01712N</td>
<td>0.04310N</td>
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<tr>
<td>Hysteresis</td>
<td>0.02970N</td>
<td>0.04120N</td>
<td>0.00532N</td>
</tr>
<tr>
<td>Interpolation</td>
<td>0.05929N</td>
<td>0.05211N</td>
<td>0.02488N</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.02825N</td>
<td>0.03362N</td>
<td>0.05430N</td>
</tr>
<tr>
<td>Expansion Combination Uncertainty</td>
<td>0.09580N</td>
<td>0.08085N</td>
<td>0.03443N</td>
</tr>
<tr>
<td>Ratio of rating force</td>
<td>0.9776%</td>
<td>0.8250%</td>
<td>0.1171%</td>
</tr>
</tbody>
</table>
DETECTION OF GRAVITY POINT MOVEMENT

In this section, we discuss a few points about some variables detected by this sensor in order to accomplish smooth manipulation. Figure 2 shows that 12 sensor elements are distributed at intervals of \( \frac{1}{12} \) on the tactile sensor. If a square rigid object contacts this sensor, we can express the gravity point of this object as follows. The object moment centering on the origin \( \mathbf{M} = (M_x, M_y, M_z) = \sum_{i=1}^{12} \mathbf{r}_i \times \mathbf{f}_i \) is expressed by using both the sensor element position vector \( \mathbf{r}_i \) and the sensor element output force vector \( \mathbf{f}_i \). If the location of the gravity point is \( \mathbf{R} = (R_x, R_y, 0) \), the object moment centering on the location of the gravity point is

\[
\mathbf{M}_G = \sum_{i=1}^{12} (\mathbf{r}_i - \mathbf{R}) \times \mathbf{f}_i = (0, 0, M_{Gz}).
\]

Therefore, we can obtain the position of gravity moment centering as \( R_x = -M_y / F_z, R_y = M_x / F_z \). Figure 7 shows a scene from the simulation. Here, the solid line is the theoretical movement of the square rigid body, and the dotted line is the simulated movement requested by the above equations. The dotted line agrees well with the solid line, demonstrating that we can find the movement of the gravity point by using this tactile sensor.

CONCLUSION

We have verified that the matrix tactile sensor is accurate and useful for a dexterous robot manipulator. We predict that the fully developed version of this sensor will see widespread use in the future.

ACKNOWLEDGEMENT

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REFERENCES